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Further study of the phase-recovering algorithm for saturated fringe patterns with a larger saturation coefficient in the projection grating phase-shifting profilometry

Eryi Hu, Yuming He*, Weiping Wu

Department of Mechanics, Huazhong University of Science and Technology, Wuhan 430074, China

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Abstract

The phase error will occur when captured fringe patterns are saturated in the projection grating phase-shifting profilometry. The phase-recovering algorithm corresponding to seven-frame phase-shifting method is deduced. The applicability ranges of phase-recovering algorithms corresponding to different phase-shifting methods are studied with different intensity saturation coefficients by a simulative method. Simulative results indicate that the phase error caused by the intensity saturation can be effectively decreased by the phase-recovering algorithm when the saturation coefficient of fringe patterns is within the applicability range of the corresponding phase-recovering algorithm. Furthermore, the applicability range of the phase-recovering algorithm will be extended with the increase of phase-shifting steps. An experimental result is presented to prove the availability of the phase-recovering algorithm.

Keywords: Phase-shifting technique; Intensity saturation; Phase error; Saturation coefficient; Phase-recovering algorithm

1. Introduction

Three-dimensional shape measurement using projection gratings with phase-shifting is a well-developed technique [1–3]. The accuracy of the phase-shifting measurement depends on systematic and random error sources. Many works dealt with the phase errors caused by the quantization error, the nonlinearity of the system and the phase-shifting error have been reported in the past years [4–11]. A phase-recovering algorithm corresponding to five-frame phase-shifting method has been proposed to solve the partial intensity saturation issue of fringe patterns [12,13]. However, the phase error caused by the intensity saturation cannot be corrected by the method [12] when the captured images have a lager saturation coefficient.

The object of this paper is to extend the applicability range of the proposed phase-recovering algorithm. Equations of the phase-recovering algorithm corresponding to seven-frame phase-shifting method are deduced. Some simulative and experimental results are presented to prove the availability of the proposed method.

2. The applicability range of the phase-recovering algorithm

In the projection grating phase-shifting profilometry, the fringe pattern intensity recorded by the CCD camera

*Corresponding author. Fax: +86 27 8754 4882
E-mail address: ymhe01@sina.com (Y. He).

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can be written as

$$I_i(x,y) = a + b\cos[\varphi(x,y) + 2\pi i/N] \quad i = 0,1,2,\ldots,N-1, \tag{1}$$

where I is the measured intensity, a is the background intensity, b is the intensity modulation amplitude, φ is the phase to be analyzed and N is the number of fringe patterns with phase-shifting.

The recorded intensity error will occur when the captured fringe patterns are saturated at some bright fringes. Subsequently, phase error is unavoidable after the phase is extracted by the conventional N-frame phase-shifting algorithm. However, if the number of unsaturated intensity values is more than or equal to three at a pixel, the phase value still can be extracted by the remnant intensity values. The improved phase-recovering algorithm corresponding to five-frame phase-shifting method has been proposed in reference [12].

A saturation coefficient K is defined to describe the saturation degree of captured fringe patterns

$$K = \frac{(a+b)}{2^n - 1}, \tag{2}$$

where 2^n-1 is the maximum quantization level of the CCD.

In order to ensure the number of unsaturated intensity values at a pixel is more than or equal to three, the saturation coefficient should be in the range [12]

$$1 < K < \frac{a+b}{a + b\cos[(1-3/N)\pi]}. \tag{3}$$

From Eq. (3) it is found that the applicability range of the phase-recovering algorithm can be extended with the increase of phase-shifting steps. The allowable maximum intensity saturation coefficients corresponding to five-frame and seven-frame phase-shifting are shown in Fig. 1(a) and (b), respectively, where $a = b$. It is obvious that the allowable intensity saturation degree for seven-frame phase-recovering algorithm is greater than that of five-frame algorithm. In addition, the allowable maximum saturation coefficient versus phase-recovering algorithm corresponding to N-frame phase-shifting methods is illustrated in Fig. 2. For instance, the allowable maximum saturation coefficients for five-frame and seven-frame phase-shifting method are 1.53 and 2.57, respectively. The corresponding saturated regions in one period are two-fifths and four-sevenths of one pitch of a grating, respectively. Thus, the phase-recovering algorithm for seven-frame phase-shifting is sufficient to solve most of the saturation issue in practical profile measurement.

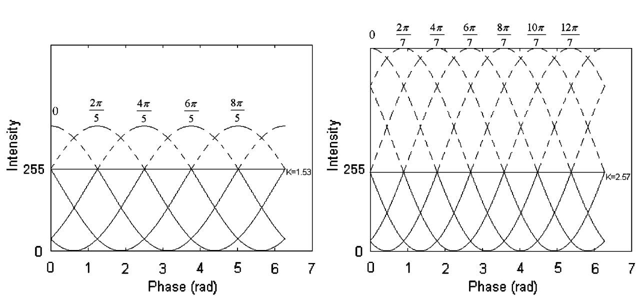

Fig. 1. Maximum saturation coefficients (a) for five-frame phase-shifting algorithm and (b) for seven-frame phase-shifting algorithm.

3. The phase-recovering algorithm corresponding to seven-frame phase-shifting method

Following the principle of the phase-recovering algorithm corresponding to five-frame phase-shifting method [12], the phase-recovering algorithm corresponding to seven-frame phase-shifting method is also deduced from the Carré technique [1]. The phase computation equations can be obtained by adding the difference of an original phase term. In these equations, m is the number of saturated intensity values at the same pixel of N-frame of fringe patterns and k is the position number of the first saturated intensity value [12].

(1) For $N = 7$, $m = 1$,

$$\varphi' = \arctan\left(\frac{2(I'_1 - I'_4)}{I'_2 + I'_3 - I'_0 - I'_5}\sin\frac{2\pi}{7}\right) - \frac{5\pi}{7}, \tag{4}$$

where $\varphi' = \varphi + 2(k+1)\pi/7$. The recovered phase can be expressed as

$$\varphi = \arctan\left(\frac{2(I'_1 - I'_4)}{I'_2 + I'_3 - I'_0 - I'_5}\sin\frac{2\pi}{7}\right) - \frac{5\pi}{7} - \frac{2(k+1)\pi}{7}. \tag{5}$$

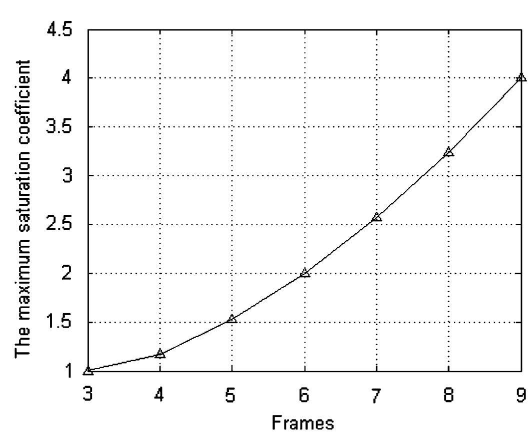

Fig. 2. Allowable maximum saturation coefficient versus N-frame phase-shifting method.